Preamble-based Successive Cancellation Scheme for the Channel Estimation in the DS-UWB System

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Abstract — In this paper, we introduce a successive cancellation channel estimation scheme based on the preamble structure suggested in the DS-UWB proposal of IEEE P802.15.TG3a. In order to improve the transmission efficiency, we reduce the length of preamble defined in the proposal without sacrificing the channel estimation performance. The gain on the transmission efficiency is discussed for different data rates. In addition, we present the bit-error-rate (BER) and packet-error-rate (PER) performances to set the appropriate number of RAKE fingers under the given requirement of the error rate criterion, applying channel estimation based on the proposed successive cancellation.

Index Terms — DS-UWB, Successive Cancellation, Channel Estimation, Transmission Efficiency.

I. INTRODUCTION

Providing very high bit rate, lower power consumption and accurate positioning capability, ultra wide band (UWB) technology is one available candidate for future short-range indoor radio communication systems.

In order to improve the multiple-access (MA) capability of UWB, UWB impulse radio technology can be combined with traditional spread-spectrum (SS) techniques. In a conventional direct sequence (DS) CDMA system, a pilot channel provides the time reference and enables coherent detection, power estimation, and power control [1]. The unmodulated spread spectrum signal in the pilot channel is broadcasted by the base station with a higher power level than the other channels. However, in the DS-UWB system proposal [2], there is no dedicated pilot channel, i.e., all the control information and data are multiplexed in the time-domain. In this case, energy loss and latency by the preamble should be minimized for optimum performance of the system.

The remainder of this paper is organized as follows. In section 2, the channel estimation scheme based on simple successive cancellation (SC) is proposed with some modifications to the operation procedure. In section 3, we describe the simulation assumptions, parameter sets, and the error rate criterion defined in the DS-UWB proposal. In section 4, we verify the performance of the SC algorithm with different preamble lengths through a computer simulation to determine the proper length of the training sequence in the preamble so as to maximize the transmission efficiency without sacrificing performance.

II. CHANNEL ESTIMATION SCHEME BASED ON SUCCESSIVE CANCELLATION ALGORITHM

The IEEE 802.15.SG3a channel model [3] for UWB transmission was derived from the Saleh-Valenzuela model where multipath components arrive in clusters. In addition, independent fading is assumed for each cluster as well as for each ray within a cluster [4]. For simplicity, we can write the discrete time impulse response of the channel as follows:

\[ h(t) = \sum_{l=1}^{L} \alpha_l \delta(t - \tau_l) \]  

where \( \alpha_l \) and \( \tau_l \) are the channel gain and delay of the \( l \)-th path, \( L \) is the number of the multipath components, respectively.

In the IEEE P802.15.TG3a DS-UWB proposal, there is a training sequence in the preamble for the purpose of channel estimation without details on the channel estimation scheme. That is, only the length of the training sequence is defined in the proposal. The training sequence in the preamble is composed of some known bits and a spread code. The chip duration of the spread code is the same as that of the data spread code. The received training sequence with length \( M \) in the preamble \( r(t) \) can be represented as

\[ r(t) = \sum_{l=1}^{L} \alpha_l s(t - \tau_l) + \omega(t) \]  

where \( s(t) \) is the training sequence transmitted and \( \omega(t) \) is a Gaussian noise [5]. We can rewrite this equation as

\[ r = s(\tau)\alpha + \eta \]  

where we take \( \eta=[\eta_1, \eta_2, ..., \eta_{M-L+1}]^T \) as a random vector with zero mean and covariance matrix \( \mathbf{C}_{\eta} = \mathbb{E}\{\eta\eta^H\} \), \( \alpha=[\alpha_1, \alpha_2, ..., \alpha_L]^T \), and \( s(\tau) \) is a matrix with entries

\[ [s(\tau)]_{m,l} = s(mT_{sp} - \tau_l) \]  

where \( T_{sp} \) is the spread symbol duration of the training sequence. We note that, for a given pair \( (\alpha, \tau) \), vector \( r \) is a Gaussian with mean \( s(\tau)\alpha \) and covariance matrix \( \mathbf{C}_{\eta} \). The covariance matrix \( \mathbf{C}_{\eta} \) depends on the interfering users. That is, for a single-user case, it is an identity matrix.

The successive cancellation channel estimation scheme is based on the autocorrelation property of the spread code in the training sequence and calculates the channel impulse response.
in an iterative manner. The SC scheme calculates the cross-correlation between the received training sequence and the known training sequence in each phase of the spread code to estimate the gains \( \{ \hat{\alpha}_l \} \) and delays \( \{ \hat{\tau}_l \} \) for the \( N \) \((N \text{ is the number of RAKE fingers})\) largest amplitudes of the cross-correlated sequence. The contribution of each estimated channel gain according to their corresponding tap is then removed from the received training sequence so as to estimate the other multipath components. If the shifted versions of the received training sequence are mutually orthogonal or the channel is one-tap, the SC algorithm is optimum. But neither of these cases is met in our system under UWB channel models, which results in sub-optimality of the successive cancellation approach. In this paper, some modifications of equations and procedure are made in order to simplify the SC algorithm in [6].

The modified procedure of the SC algorithm is given in the following steps:

**Step 1** Set \( l=1 \) and \( r_0 = r \).

**Step 2** Perform a search for the strongest tap \( \tau_l \) and \( a_l \) using (5) and (6), and store the strongest amplitude with the corresponding time delay as reference for Rake finger allocation and coherent detection.

\[
\hat{\tau} = \arg \max_{\tau} \left\{ \frac{\mathbf{s}^H (\theta) \mathbf{C}_{\eta}^{-1} \mathbf{r}}{\mathbf{s}^H (\theta) \mathbf{C}_{\eta}^{-1} \mathbf{s} (\theta)} \right\} \quad (5)
\]

\[
\hat{\alpha} = \frac{\mathbf{s}^H (\hat{\tau}) \mathbf{C}_{\eta}^{-1} \mathbf{r}}{\mathbf{s}^H (\hat{\tau}) \mathbf{C}_{\eta}^{-1} \mathbf{s} (\hat{\tau})} \quad (6)
\]

Here, \( \hat{\tau} \) and \( \hat{\alpha} \) are estimated channel delay and impulse response, respectively.

**Step 3** Remove the contribution of the estimated path from the received training sequence as in (7). Compared with [6], this step is simplified by considering the strongest path only.

\[
r_{(l+1)} = r_{(l)} - \hat{\alpha}_l \mathbf{s} (\hat{\tau}_l) \quad (7)
\]

**Step 4** If \( l \) is smaller than the number of Rake fingers, repeat from **Step 2** with matrix \( r_{(l+1)} \) instead of \( r \) in (5) and (6).

Due to its good autocorrelation property and simplicity, we choose the m-sequence as a spread code to generate the training sequence in the preamble in this paper. The period of the spread code should be set to be much longer than the maximum time dispersion of the channel.

### III. Assumptions and Parameter Sets

We consider a single-user and a perfectly synchronized DS-UWB system, i.e., no multi-user interference in the system. We do not take into account the distortions from the antenna and nonlinear hardware. The signal flows at the transmitter and receiver sides are shown in Fig. 1. The functions of the puncture and depuncture are used only in the case of generating convolutional code of rate 3/4.

![Fig. 1. The PHY signal flow.](image)

All the simulations in this paper are conducted using the parameter set of 55 Mbps data rate in the lower operating band, according to the IEEE P802.15.TG3a DS-UWB proposal [2].

The explicit settings of the parameters are described below:

- The uncoded data rate \( R_b \) is 55 Mbps.
- We use convolutional code as the error correction code, whose rate is 1/2 and constraint length is 7.
- The transmitted pulses are modulated using BPSK.
- We use m-sequence as the spread code of the training sequence in the preamble which is generated by linear feedback shift registers. The period is 255 chips and the generation polynomial is as following.

\[
C_p (x) = 1 + x^2 + x^3 + x^4 + x^8 \quad (8)
\]

- IEEE P802.15.SG3a UWB channel model is adopted. Here, the number of multipath components is equal to \( N_{\text{PULTR}} \) defined in the IEEE 802.15.SG3a channel model [3].
- All of the UWB channel models were simulated using 100 channel realizations for each \( E_b/N_0 \).

We use the error rate criterion to evaluate the PER performance of the DS-UWB system. The error rate criterion shall be a PER of less than 8\% with a frame body length of 1024 octets [2].

### IV. Performance Validation

The system structure with the proposed successive cancellation channel estimation scheme is shown in Fig. 2. Since the chip rate of the spread code for the training sequence is the same as the rate of the data spread code, we define the
transmission efficiency as in (9), where the lengths of the packet will include the length of the preamble, the PHY header, the MAC header, HCS, and user data. The transmission efficiency varies for different cases of DS-UWB system data rate.

\[
\text{Tx Efficiency} = \frac{\text{Length of User Data (chips)}}{\text{Length of Packet (chips)}} \quad (9)
\]

In Fig. 3, we vary the length of the training sequence in the preamble from 1020 chips to 6120 chips and use an 8-finger MRC RAKE receiver with the channel estimation method of the proposed successive cancellation algorithm to obtain BER performance under channel model (CM) 4. The performance of the DS-UWB system with the SC algorithm based on the training sequence with lengths of 2040 chips, 4080 chips, and 6120 chips is nearly the same at the target BER of \(10^{-4}\). However, at the same target, the case of the training sequence with a length of 1040 chips suffers roughly 0.5 dB degradation relative to the other cases. Therefore, the training sequence in the preamble with a length of 2040 chips is deemed satisfactory in terms of performance and transmission efficiency. Hence, we propose a reduction of the length of the training sequence in the IEEE P802.15.TG3a proposal from 6144 chips to 2040 chips.

Based on equation (9), the transmission efficiency for the short preamble structure and the parameter sets in the lower operating band defined in [2] can be given as follows: The PHY packet is composed of a preamble, a frame body of 1024 octets, and other control information bits. The transmission efficiency then becomes 96\%, 92.3\%, 85.8\%, 75.1\%, 50.1\% and 33.4\% for the data rates of 28 Mbps, 56 Mbps, 110 Mbps, 220 Mbps, 660 Mbps, and 1320 Mbps, respectively. After reducing the length of the training sequence in the preamble used for channel estimation to 2040 chips used for channel estimation, we recalculate the transmission efficiency for the above cases, obtaining transmission efficiency improvement of 1\%, 1.8\%, 4.1\%, 5\%, 7.2\%, and 6.7\%. The improvement in the transmission efficiency in the case of high data rates is much larger than that for low data rates.

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Fig. 4 presents the PER performance of perfect and SC channel estimation algorithms with different finger numbers of a MRC RAKE receiver under CM 1. The training sequence in the preamble with the proposed length of 2040 chips is used to estimate the channel. From the simulation results, we find that the 16-finger RAKE receiver outperforms the 8-finger RAKE receiver by only about 0.1 dB at the error rate threshold, and thus the 8-finger RAKE receiver is recommended. We also find that the difference in the PER performance between the perfect and SC channel estimation algorithms is less than 0.1 dB at the error rate threshold for all four RAKE finger cases.
In this paper, we propose a training sequence for the preamble in the IEEE P802.15.TG3a DS-UWB proposal. The proposed training sequence has a shorter length of 2040 chips compared with the length of 6144 chips in the proposal. A simplified version of the successive cancellation scheme is also proposed for application to channel estimation. Through assessment of the BER and PER performances of the successive cancellation channel estimation scheme based on a training sequence with a length of 2040 chips in the preamble, we find that the successive cancellation channel estimation scheme provides non-degraded performance compared to the case of the original training sequence with a length of more than 6 thousand chips. By reducing the preamble length, the transmission efficiency is improved by at least 1% for the case of 28 Mbps data rate and at most 7.2% for the case of 660 Mbps data rate. The increase in the transmission efficiency can be interpreted as QoS improvement by reduced latency.